Patterns of Dissolved Oxygen, Productivity and Respiration in Old Woman Creek Estuary, Erie County, Ohio during Low and High Water Conditions

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Abstract: Old Woman Creek wetland is composed of a stream and freshwater estuary and may act as a sink or transformer of nutrients entering Lake Erie. Primary productivity and respiration are indicators of ecosystem level trophic conditions and may be linked to the estuary's effectiveness as a nutrient sink or transformer. Old Woman Creek National Estuarine Research Reserve has been collecting water chemistry data at 15 minute intervals using data loggers since 1995. Both diel and seasonal trends in water temperature, dissolved oxygen, and water depth at selected sites in the creek and estuary were related to physical and biological processes. Daily primary productivity and respiration were estimated from diurnal changes in dissolved oxygen under both high and low water conditions. Mean water depth was higher in 1997 and 1998 (0.94-1.2 m) than in 2003 and 2004 (0.5-0.66 m). Water temperature was generally 1-2° C higher in the open lower estuary and mouth than in the creek and upper estuary which is more shaded. Typical diurnal fluctuations in dissolved oxygen ranged from less than 20% to greater than 150% saturation. Primary productivity rates in the creek and upper estuary were lower (0.5-3.5 gO_2/m^2/day) than in the lower estuary sites (2.0- 10.1 g O_2/m^2/day). Through both periods of high water and low water, the GPP/R ratio was less than one, thus negating our hypothesis that the ratio would be greater than 1 during high water years when the estuary was primarily an open water system.

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INTRODUCTION

Primary productivity and respiration vary widely across different ecosystems and are indicators of ecosystem trophic conditions. If primary productivity exceeds respiration, the system is autotrophic and internal production of organic matter dominates. When respiration exceeds primary productivity, the system is heterotrophic and relies on an outside source of organic matter. Diurnal changes in dissolved oxygen reflect system metabolism and have been used to determine primary productivity and respiration for many ecosystems (Odum 1956, Odum and Hoskins 1958, Mitsch and Kaltenborn 1980, Caffrey 2003).

In most freshwater wetlands, phytoplankton is considered a minor component (Mitsch and Gosselink, 1993). In earlier studies of the coastal marshes along Lake Erie, phytoplankton was considered a significant, but not the major source of fixed carbon (Herdendorf, 1987). In an earlier study, Reeder (1990) determined that phytoplankton was the major source of carbon in Old Woman Creek estuary, resulting in a grazer based food web. Shallow, plankton-dominated wetlands, like Old Woman Creek (OWC) near Lake Erie, are ideal systems to use diurnal patterns in dissolved oxygen because, being shallow, they have a narrow euphotic zone with high chlorophyll and dramatic oxygen fluctuations (Mitsch and Reeder 1989). Coastal wetlands like OWC estuary protect Lake Erie by intercepting nutrients and other pollutants before they enter the lake. Ecosystem metabolism may be linked to the estuary's effectiveness as a nutrient sink or transformer (Klarer and Millie 1989 , Heath 1987, Mitsch and Reeder 1991).

Changing water levels in Great Lakes have had a dramatic impact on the flora in the adjacent coastal wetlands (Keddy and Reznicek 1986). During the years of high Lake Erie water levels (1970s-1999), the OWC estuary was primarily an open water system with aquatic macrophytes, particularly *Nelumbo lutea* covering about one-third or less of the surface of the estuary (Whyte 1996, Herdendorf et al. 2006). With declining lake water levels beginning in 1999, the estuary shifted from an open water system to one dominated by emergent vegetation (Trexel-Kroll 2002). Open water areas of the estuary declined from about 70% of the surface area of the estuary during the mid 1990s to less than 30% of the surface area in 2000 (Herdendorf et al. 2006).

The drop in water levels and the resulting shift in vegetation should be reflected in the production/respiration ratio in the estuary. Before the drop in water levels, the estuary was dominated by open water and plankton communities (Reeder 1990; Herdendorf et al. 2006). After this drop, emergent macrophytes became the dominant community. This should result in a shift from a grazer based food web to a detrital based food web. In such a food web, the production/respiration ratio would be lower than in a grazer based system, as the primary source of organic carbon is outside the water column and therefore does not contribute to the measured production. It is hypothesized that with the drop in water levels in 1999/2000, and the subsequent dominance of aquatic macrophytes, the production/respiration ratio would decrease as the estuary shifted from a grazer based food web to one that was detrital based.

Study Site

Old Woman Creek wetland is a National Estuarine Research Reserve (NERR) located near the southern most point of the south shore of Lake Erie, 5 km east of Huron, Ohio (Fig. 1). It is a freshwater estuary with diverse habitats, including marshes, a swamp forest, open waters, and a barrier beach. The mouth of the creek is controlled by this barrier beach, which responds to storms on Lake Erie and in the watershed. During periods of moderate to high rainfall, the mouth is normally open to Lake Erie, but in periods of low rainfall, the barrier beach may close the mouth, thus isolating the wetland from Lake Erie. The mouth is closed about 40% of the time, although this varies greatly from year to year (Herdendorf et al. 2006). The estuary drains a watershed of 69 km^2, which is primarily row crop agricultural lands. The high proportion of agricultural activity in the watershed has resulted in a wetland that is highly eutrophic. The high productivity of the wetland is demonstrated in the diurnal changes in dissolved oxygen that have been recorded in the estuary (<20% to > 150% Herdendorf et al. 2006).

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As part of the National Estuarine Research Reserve System, Old Woman Creek NERR has participated in the System Wide Monitoring Program (SWMP), since the program's inception. The purpose of this intensive water quality data collection program is to determine the long-term changes and the short-term variations in representative estuaries along the coasts of the United States (Wenner 2001). Water quality data, including dissolved oxygen, depth, and temperature, are collected every 15 minutes using data

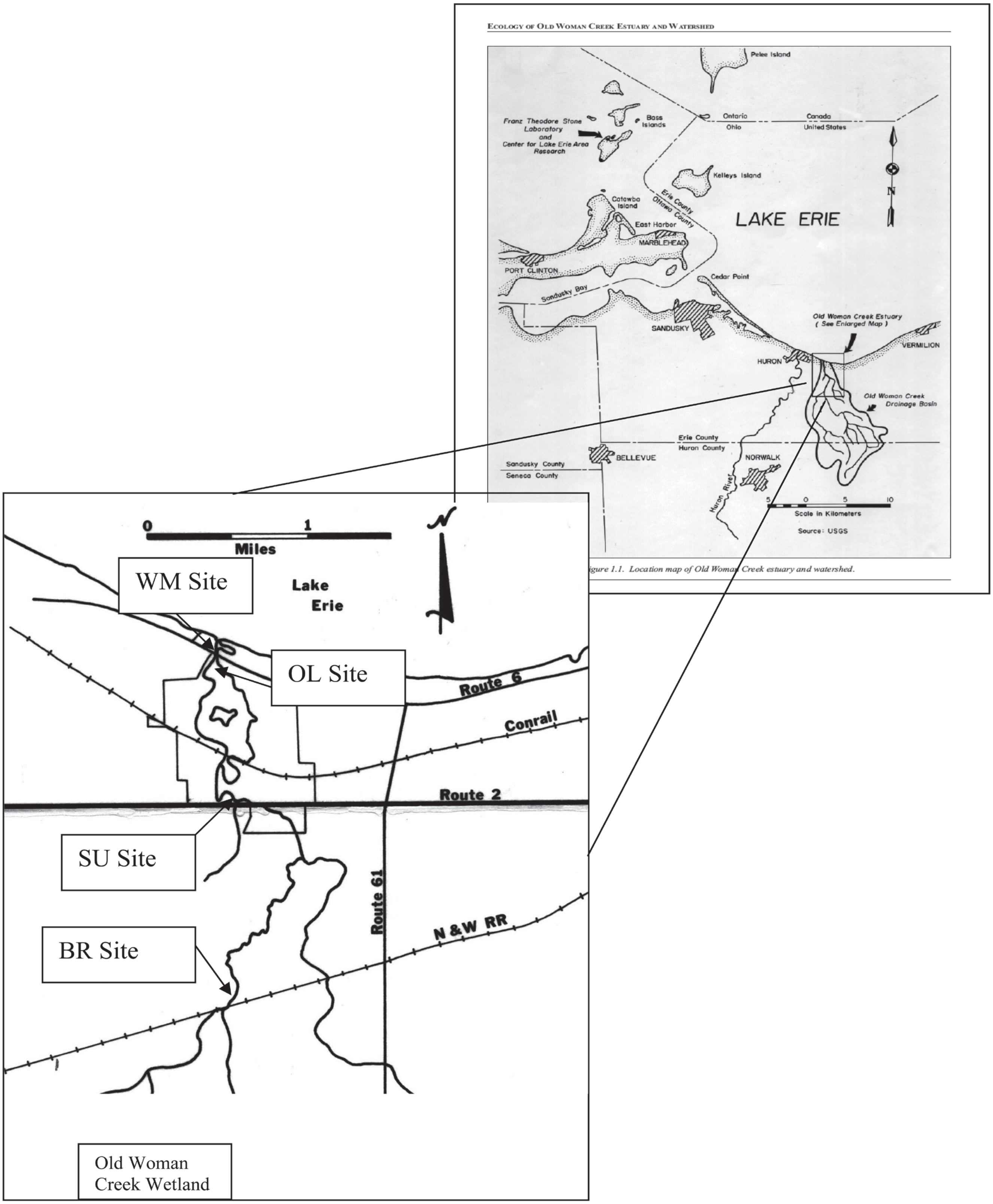


Figure 1. Location of sites BR, SU, OL, and WM within Old Woman Creek. Area map from Herdendorf CE, Klarer DM, Herdendorf RC. 2006. (permission granted)

loggers. This program began in 1995 at two sites in the estuary: site SU in the upper estuary and site WM in the lower estuary near the mouth of the estuary where the estuary empties into Lake Erie. In 2001, two more sites (BR and OL) were added to the program. Site BR is located in the Old Woman Creek proper just upstream of the first riffle zone above the estuary. Site OL is located in the Lower Estuary upstream from the WM site. The locations of the four sites are illustrated in Figure 1.

MATERIALS AND METHODS

Diurnal temperature patterns were studied and productivity and respiration rates were calculated from changes in dissolved oxygen using data collected in the OWC SWMP. Water quality data from April to October were evaluated for two years (1997 and 1998) when Lake Erie water levels were high and two years (2003 and 2004) when Lake Erie water levels were much lower and closer to the long term average. Trends in water temperature (T) and dissolved oxygen (DO) at selected sites in the creek and estuary are described and related to physical and biological processes. Seasonal effects (early spring vs. late summer), and effects of lake level on productivity and respiration were investigated.

Water quality data were collected every 15 minutes using Yellow Springs Instruments Model 6000 (1997 and 1998) and Model 6600 EDS (2003 and 2004) Data Loggers. Parameters measured include: temperature (T), pH, dissolved oxygen (DO), depth, turbidity, and specific conductivity. The loggers were normally changed every two weeks during the late spring, summer, and early autumn. In the early spring and late autumn, the loggers were changed every three weeks. Weather parameters were also measured at the Reserve using a Campbell Scientific Weather System. The weather parameters include: precipitation, photosynthetic active radiation (PAR), air temperature, barometric pressure, relative humidity, and wind speed and direction.

Trends in depth, water temperature, and dissolved oxygen were evaluated at four sites located in the Creek Proper (BR), the Upper Estuary (SU), Lower Estuary (OL), and the mouth (WM). Seasonal effects were determined for BR, SU, and OL sites during early spring (April) and late summer (August) in 2004. Trends were then compared at sites SU and WM to determine the impact of Lake Erie water levels on productivity in the estuary.

Productivity and respiration were estimated from changes in dissolved oxygen at all four sites (BR, SU, OL, and WM) during 2003 and 2004 and at two sites (SU and WM) during 1997 and 1998. Specifically, Gross Primary Productivity (GPP), Net Productivity (NP), Hourly Respiration Rate (HRR), and Respiration (R) were calculated for each day. Monthly and yearly averages were compiled from daily data.

In this study, oxygen diffusion into and out of the atmosphere was not calculated because Reeder and Mitsch (1989) and Reeder and Binion (2001) using the diffusion dome method (Copeland and Duffer, 1964) had earlier determined that diffusion rates were negligible.

Net Productivity was determined by summing the oxygen flux during daylight hours (0600 to 1800).

Net Productivity (g O_2/m^2/day)
NP = $\Sigma (\Delta[O_2]/\Delta t)$ * depth (during daylight: 0600 to 1800) ....(1)

Hourly Respiration Rate was determined by summing the oxygen flux during night time hours when no photosynthesis occurs and then dividing by the number of hours. In previous studies (Caffrey 2003, Mitsch and Reeder 1989, Reeder and Mitsch 1989), the night time interval used to evaluate the hourly respiration rate was 1800 to 0600. But during summer months, the sun sets as late as 2100 and rises as early as 0500. This 12-hour interval includes photosynthetic periods and thus would underestimate the respiration rate. In this study, hourly respiration rate was determined for a night time interval of 2200 to 0300 to ensure that no photosynthesis occurs. The results of this method were compared to results based on a night time interval of 1800 to 0600 using a paired two sample student t-test.

Hourly Respiration Rate (g O_2/m^2/hour)
HRR = -1* ($\Sigma (\Delta[O_2]/\Delta t)$ * depth) / time (during darkness: 2200 to 0300) ....(2)

Gross Primary Productivity is an indication of system metabolism and is a measure of total photosynthesis. Gross Primary Productivity was determined by adding respiration during daylight hours (0600 to 1800) to Net Productivity.

Gross Primary Productivity (GPP) (g O_2/m^2/day)
GPP = Net Productivity + Respiration Rate x 12 hours ....(3)

Respiration was determined from the respiration rate, as follows:

Respiration (R) (g O_2/m^2/day)
R = Respiration Rate x 24 hours .....(4)

Gross Primary Productivity was compared to **Respiration** by:

P / R Ratio
P/R = GPP / R .....(5)

In ecological systems, respiration rate and gross primary productivity are greater than zero and net productivity is less than gross primary productivity. These conditions may not be met when physical processes control oxygen dynamics, the signal to noise ratio of the oxygen sensor is low or other confounding factors occur (Caffrey 2003). Therefore, when the calculated respiration rate was negative (HRR<0) or the calculated net productivity exceeded gross primary productivity (NP>GPP), the data point was omitted. The percentage of data points that met this criteria were tabulated and presented on an annual basis. Monthly and yearly average values for GPP, NP, HRR, R, and GPP/R were calculated. The GPP/R ratio was also calculated based on a night time interval of 1800 to 0600 and compared with our GPP/R ratio using a paired two sample t-Test. Correlations of monthly average water temperature to monthly average gross primary productivity, hourly respiration rate, and productivity to respiration ratio were determined using Least Squares Linear Regression Analysis for one independent variable (temperature). Positive slopes indicate a positive correlation with temperature. Values of the coefficient of determination (R^2) greater than 0.14 (Johnson 1972) are evidence of correlation. Statistical differences in the mean GPP and GPP/R for low and high water years were determined using the two sample t-Test assuming equal variances. The statistical analysis was performed with Microsoft Excel Data Analysis Tools.

RESULTS

Depth

Water depth was measured in the upper estuary from April to October in representative high water level years (1997, 1998) and low water years (2003, 2004). In the upper estuary (SU), the average water level was nearly twice as deep during high water years (Table 1).

Water Temperature

In the Old Woman Creek system, the coolest monthly average water temperatures during the sampled period (April-October) occurred in April (eg. 9.6°C at SU site, April 1997) and the warmest temperatures occurred in July or August (eg. 25.4°C at WM site, July 1998) during the study period. Waters in the upper estuary are generally confined to a distinct channel, while in the lower estuary, the waters spread out over a large area. This greater surface area to volume ratio in the lower estuary, plus the fact that the two sites in the lower estuary are exposed to direct sunlight while those in the upper estuary and creek proper were not, may explain why water temperatures were generally 1 – 2°C higher in the open lower estuary than in the creek and upper estuary (Fig. 2).

Water temperature increased seasonally from April to August. In April 2004, the average monthly water temperatures in the stream (BR) and upper estuary (SU) were 10.3°C and 10.5°C, respectfully and 11.2°C in the lower estuary (OL). Average water temperature in August was about 10°C higher at each site (19.4°C at BR, 20.8°C at SU and 22.8°C at OL).

Diurnal temperature variations were observed at all sites for April 2004 and August 2004. Precipitation disrupted the diurnal temperature pattern in April 12-14, 2004 (Fig. 2). In April, the largest fluctuation (5-9°C) occurred in the lower estuary (OL) due to the exposed nature of the site. Diurnal temperature fluctuation in the creek (BR) was moderate (5-6°C) and smallest in the upper estuary (SU) (2-4°C) where the data logger is positioned under the highway bridge. In August, the diurnal temperature fluctuations at all three sites were smaller than in April, but the same general pattern of highest differences in the lower estuary were observed (OL: 4-6°C, SU: 2-4°C, and BR: 1-2°C).

Dissolved Oxygen

Dissolved oxygen concentrations decreased as temperature increased exhibiting the expected physical property of decreased gas solubility with increasing temperature (Cornell 2007). For example, at the BR site in April, 2004, the average DO was 11.3 mg/L at 10.3°C while in August, the DO decreased to 8.1 mg/L at 19.4°C.

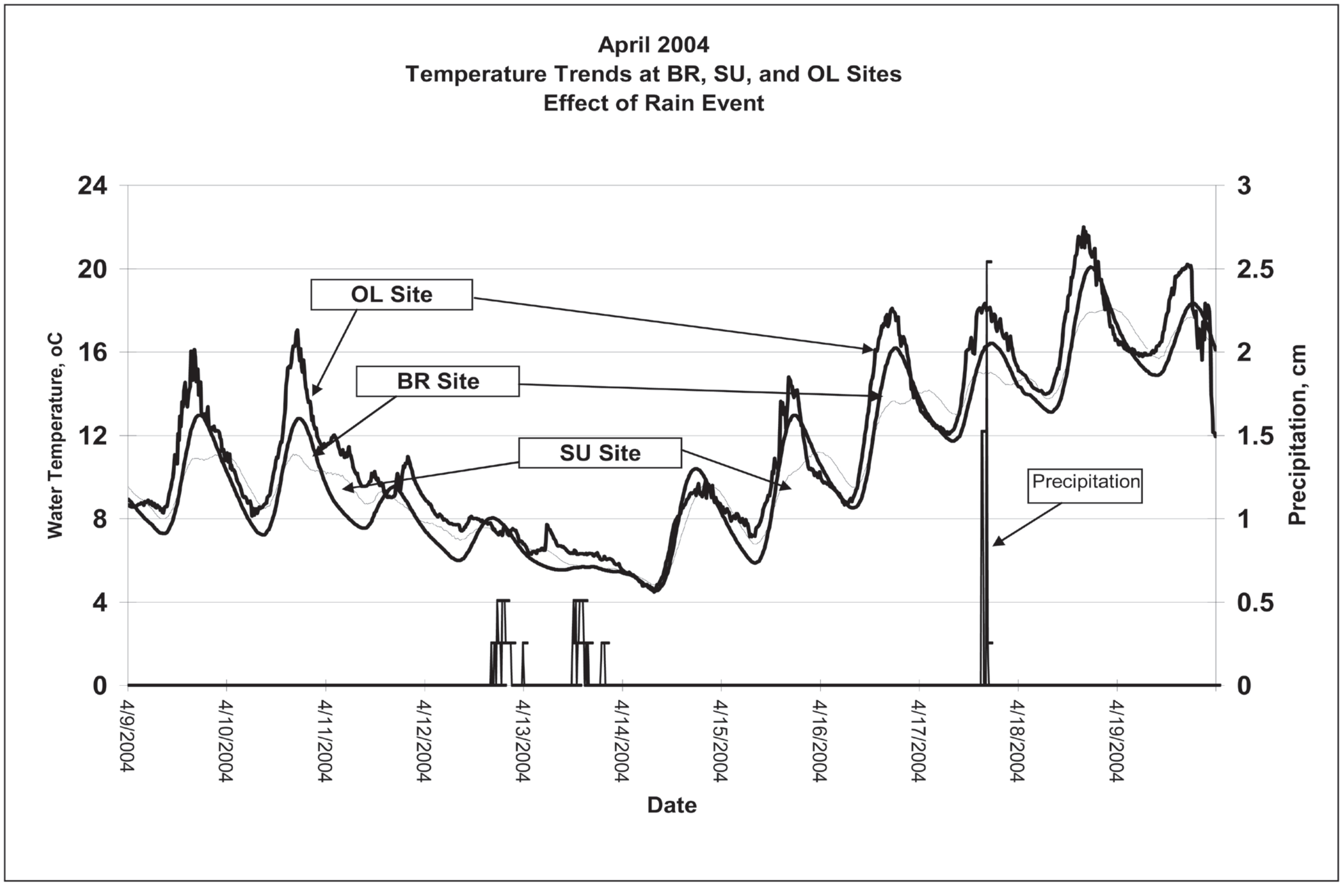
Dissolved oxygen exhibited strong diurnal fluctuations at all sites during the study period (Cornell 2007) due to photosynthesis and respiration processes. Rain events produced a sharp increase in water depth in the creek site BR (Cornell 2007) and disrupted the diurnal DO pattern (Fig. 3) through hydrodynamic mixing.

In April 2004, the creek (BR) typically exhibited a diurnal rise in DO (Fig. 3). Diurnal fluctuation in this flowing system suggests that benthic algae are a major component of the biota at this site. Diurnal fluctuations in the estuary, both upper and lower, were also quite pronounced, and seem to be the result of plankton activity. Fluctuations in the lower estuary were often smaller and noisier than in the upper estuary, possibly due to intrusion of lake water, which is generally close to 100% saturation (Herdendorf et al 2006).

Table 1

Annual averages of Temperature, Depth, Respiration Rate, Gross Primary Productivity, Production/Respiration Ratio, and Percentage of Data that meets criteria (HRR>0, GPP>NP) for inclusion.

Year	Site	Water Level	Depth (meter)	Temperature (°C)	Respiration Rate (g O_2/m^2/hr)	GPP (gO_2/m^2/day)	GPP/R	Percentage of Data Included (%)
1997	SU	High	1.078	16.800	0.1077	1.940	0.751	46.15
1998	SU	High	1.181	19.174	0.1760	3.164	0.749	50.95
2003	SU	Low	0.530	17.089	0.0680	1.376	0.843	63.33
2004	SU	Low	0.709	17.355	0.0662	1.288	0.811	68.22
1997	WM	High	NA	18.220	0.1968	3.454	0.731	64.57
1998	WM	High	NA	20.359	0.3180	6.538	0.857	69.67
2003	WM	Low	NA	18.941	0.2130	4.182	0.818	75.24
2004	WM	Low	NA	18.905	0.3262	5.943	0.759	67.77
2003	OL	Low	NA	18.982	0.2766	5.360	0.807	69.29
2004	OL	Low	NA	18.765	0.3842	7.493	0.813	67.73
2003	BR	Low	NA	16.320	0.0283	0.685	1.010	54.79
2004	BR	Low	NA	16.400	0.0255	0.529	0.870	51.37



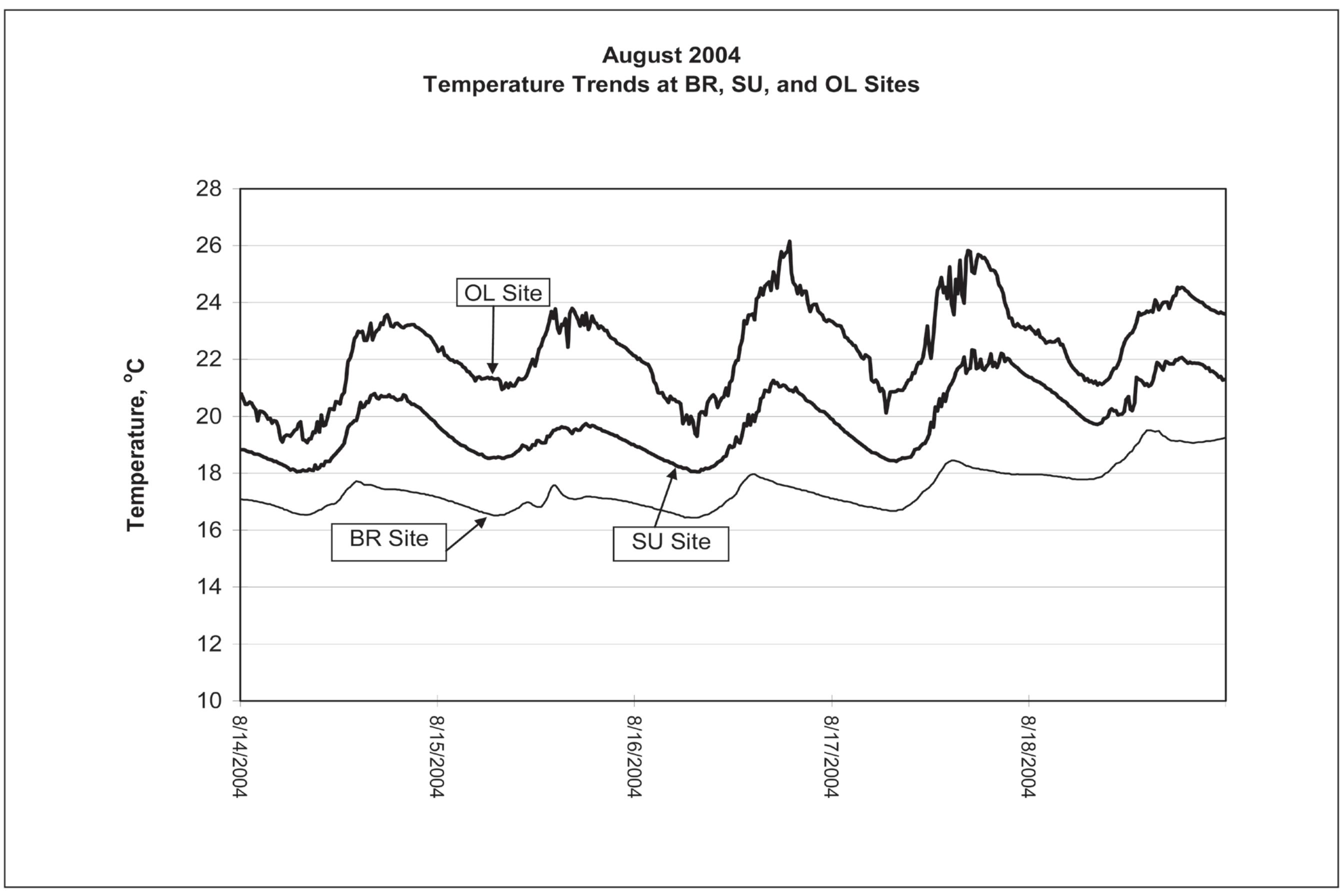
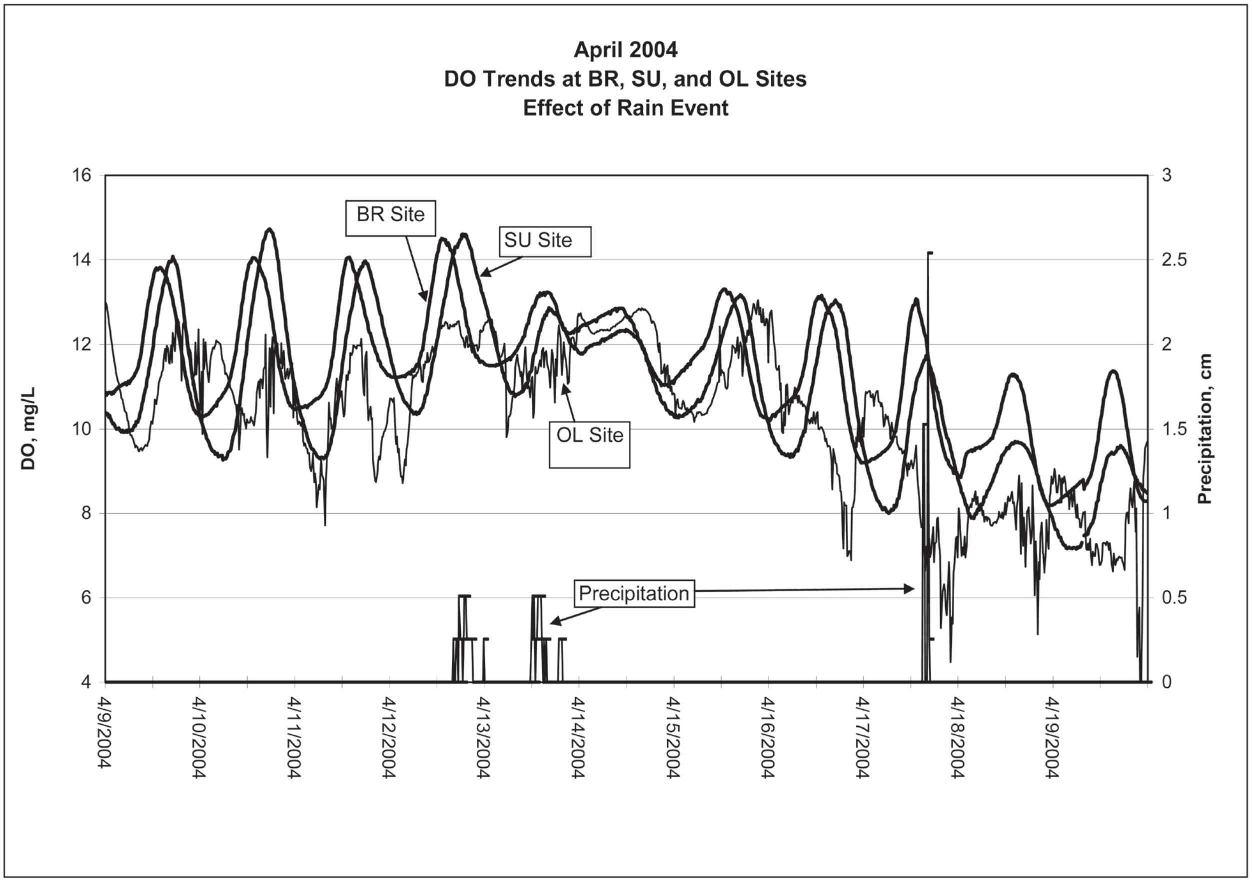


FIGURE 2. Temperature trends at sites BR, SU, OL during April 2004 and August 2004.



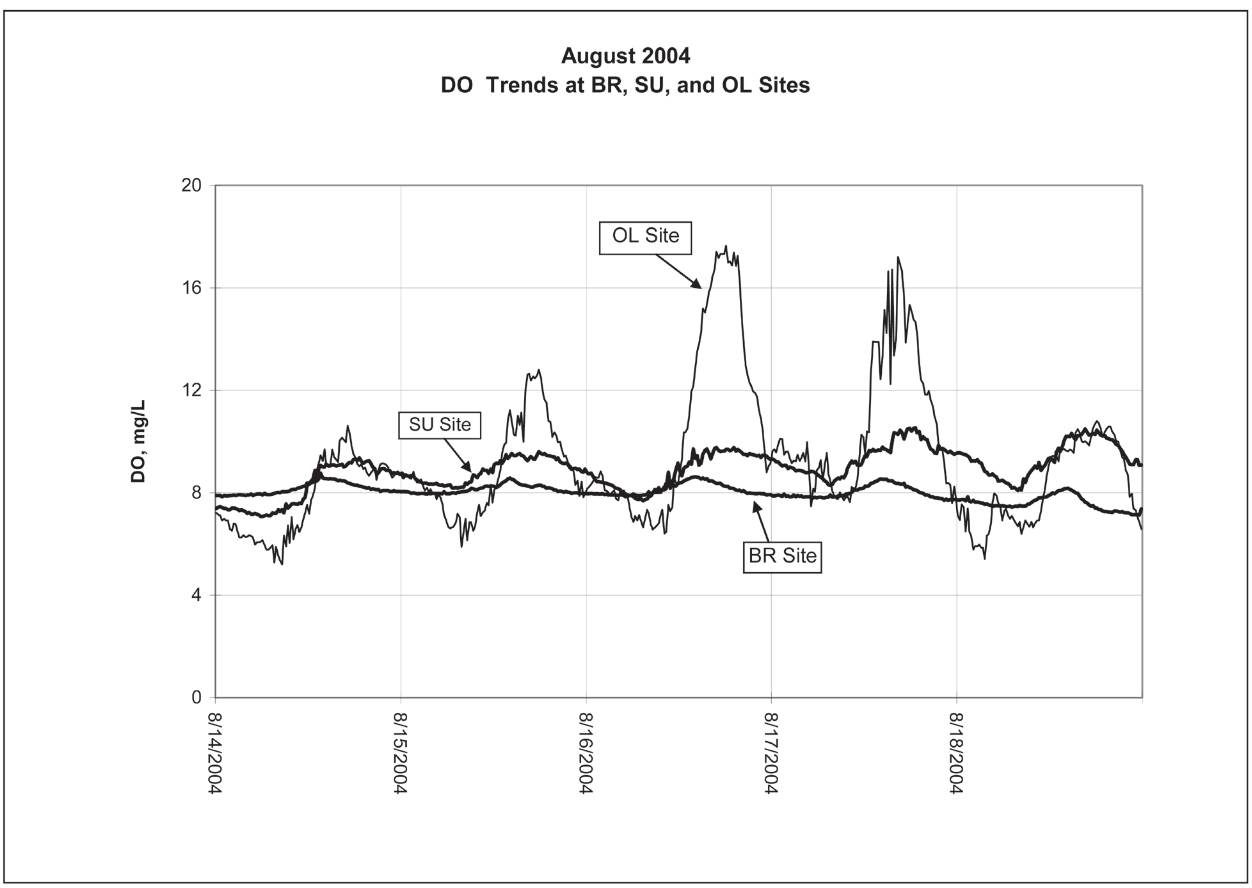


FIGURE 3. Dissolved oxygen trends at site BR, SU, OL during April 2004 and August 2004.

In August 2004, diurnal fluctuations in the lower estuary were greater than in the upper estuary reflecting the more exposed nature of the lower estuary (Fig. 3). In the creek (BR) and upper estuary (SU), diurnal fluctuations in DO decreased substantially, indicating a decrease in biological activity. In the lower estuary increased water temperatures coupled with increased light energy and higher phytoplankton and benthic algal communities caused these increased oxygen fluctuations (Cornell 2007).

Productivity and Respiration

Net productivity, respiration rate, gross primary productivity and respiration were calculated for each day that data were collected during April through October in 1997, 1998, 2003 and 2004. Monthly average values of gross primary productivity (GPP), respiration rate (HRR) and the GPP/R ratio (April to October) are illustrated in Figures 4-7 respectively. On average, 46% to 75% of the data met our screening criteria (HRR>0, GPP>NP) for good data (Table 1).

Gross primary productivity (Fig. 4) was lower in the stream (BR) and upper estuary (SU) than in the lower estuary (OL) and mouth (WM). GPP in the stream ranged from 0.26 to 1.14 g O_2/m^2 while in the lower estuary it ranged from 2.04 to 10.15 g O_2/m^2. Respiration rate followed the same pattern: lower in the stream and upper estuary site and higher in the lower estuary and mouth (Fig.5). For example, respiration rate in the stream varied from 0.013 to 0.073 g O_2/m^2/hr while in the lower estuary it varied from 0.14 to 0.50 g O_2/m^2/hr.

Productivity and respiration variations between sites within the study area may be due to localized differences in solar radiation and water temperature. The stream and upper estuary sites are more shaded and water temperature at these sites is 1-2^0 C lower than the more open lower estuary sites (OL, WM) resulting in the lower productivity and respiration of the former. Additionally, hydrodynamic disturbances are more likely to occur in the flowing, benthic dominated stream site BR and the riverine–like upper estuary site SU. The lower estuary sites (OL and WM) are more broad and lake–like with larger phytoplankton populations (Klarer and Millie, 1994). The mouth (WM) has slightly lower GPP and respiration rates than the OL site perhaps due to regular lake incursion and wave action.

A seasonal effect was apparent in the monthly average gross primary productivity, net productivity and respiration for April and August 2004 (Fig. 8). Gross primary productivity dropped slightly in the creek (BR) (0.96 → 0.32 g O_2/m^2/day) and upper estuary (SU) (2.37 →1.13 g O_2/m^2/day) in August 2004 as compared to April 2004. However, the opposite occurred in the lower estuary (OL) where gross primary productivity rose from April to August (4.52 → 10.59 g O_2/m^2/day). Similar seasonal trends occurred during 1997, 1998, and 2003 (Fig. 5).

Correlation of gross primary productivity with temperature using least squares linear regression analysis mirrors the seasonal trends in gross primary productivity (Table 2). Gross primary productivity correlated positively with temperature for the lower estuary (OL) and mouth (WM) sites ($R^2 > 0.2$). However, in the creek (BR) the gross primary productivity was higher in the spring than in August for both years tested and correlation with temperature yielded a negative slope ($R^2 = 0.41$). The gross primary productivity in the upper estuary (SU) did not have a consistent seasonal trend over the four years and correlates poorly ($R^2 = .07$) with temperature.

Trends in average monthly respiration were similar to trends in gross primary productivity for April and August, 2004 (Fig.

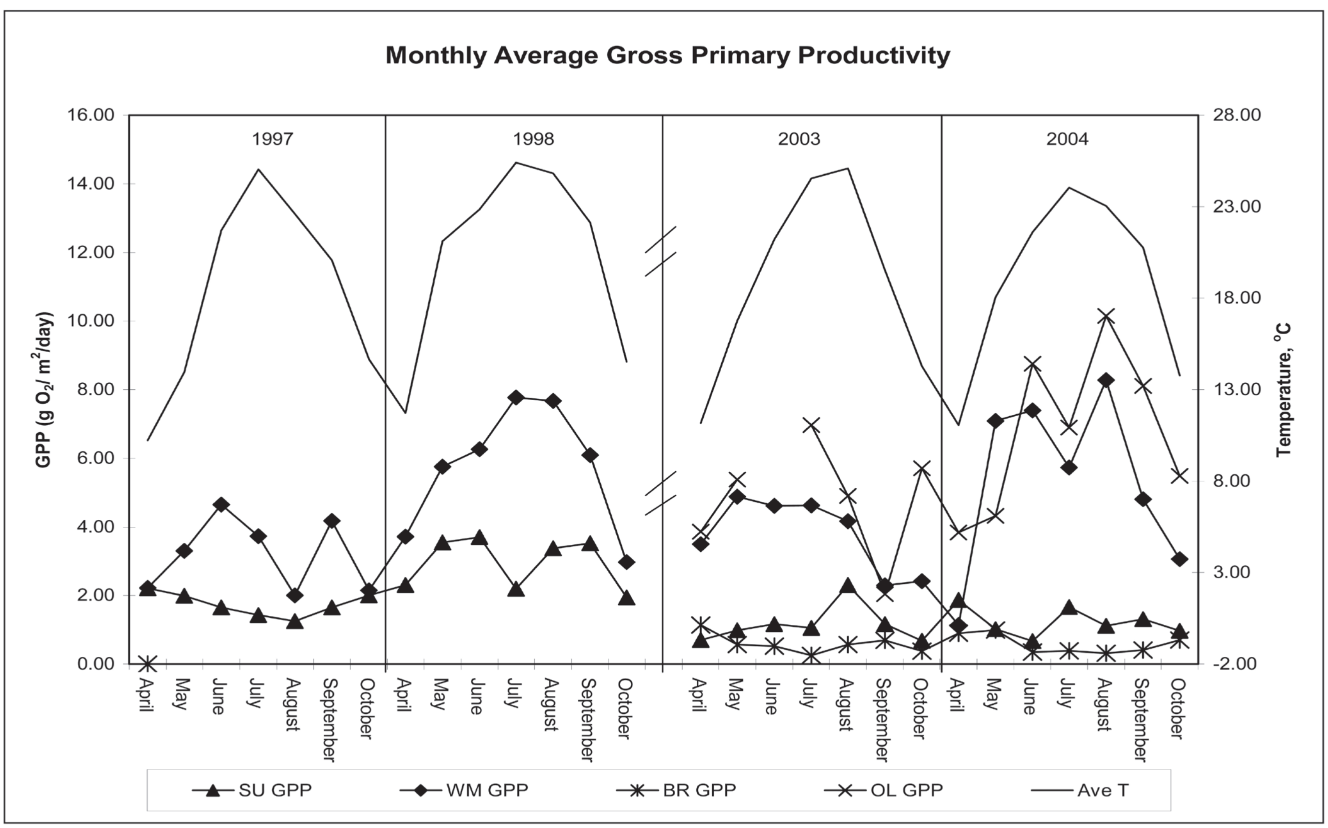


Figure 4. Monthly average gross primary production at sites SU and WM during 1997 and 1998 and at sites BR, SU, OL, and WM during 2003 and 2004 and average monthly water temperature fromsite SU.

8). Respiration was highest in the lower estuary and lowest in the creek for both months. In the creek (0.52 → .36 g O_2/m^2/day) and upper estuary (1.8 → 1.3 g O_2/m^2/day), respiration dropped from April to August. However, in the lower estuary (5.4 → 12 g O_2/m^2/day), respiration increased from April to August. These same trends were reflected in all years tested for the lower estuary, mouth and creek as seen in Figure 5.

Monthly average respiration rate increased with temperature for the lower estuary (OL) and the mouth (WM) and thus was typically higher in August than in April. Respiration rate correlated positively with temperature ($R^2 > 0.35$) (Table 2). Respiration rate in the creek (BR) was negatively correlated with temperature (R^2=0.34) and thus, had a lower respiration rate in August than in April. The upper estuary (SU) again did not have a consistent trend over the years evaluated (Fig. 5) and did not correlate with temperature (Table 2). Yearly averages for gross primary productivity and respiration rate values were higher in the lower estuary and mouth, than in the upper estuary and creek (Table 1).

The estuarine system cycles through high and low Lake Erie water levels. In the upper estuary (SU), the average respiration rate (Table 1) for the high lake level years (1997, 1998) exceeded the average respiration for low lake level years (2003, 2004). In the high water years the average respiration was 3.4056 g O_2/m^2/day compared to 1.6104 g O_2/m^2/day for low water years. Also, the average gross primary productivity was higher during high lake levels compared to low lake levels (2.5520 g O_2/m^2/day and 1.3321 g O_2/m^2/day, respectively). At the estuary mouth (WM), the average respiration for high lake levels was about the same as for low lake levels (6.1776 g O_2/m^2/day and 6.4704 g O_2/m^2/day, respectively)

Table 2

Correlation between temperature and gross primary productivity, respiration and production/respiration ratios.

Site	Least Squares Correlation with Temperature (T)	
	Gross Primary Productivity (GPP)	
BR	**GPP = -0.0445*T + 1.3109**	**R2 = 0.4141**
SU	GPP = 0.0527*T + 0.8402	R2 = 0.0713
OL	**GPP = 0.2521*T + 1.1696**	**R2 = 0.2795**
WM	**GPP = 0.2496*T - 0.2592**	**R2 = 03919**
	Respiration Rate (RR)	
BR	**RR = -0.0023*T + 0.0618**	**R2 = 0.3421**
SU	RR = 0.003*T + 0.0426	R2 = 0.0801
OL	**RR = 0.0136*T + 0.062**	**R2 = 0.03842**
WM	**RR = 0.0121*T + 0.0246**	**R2 = 0.3536**
	GPP/R Ratio	
BR	GPP/R = -0.0125*T + 1.2867	R2 = 0.0138
SU	GPP/R = -0.0007*T + 0.798	R2 = 0.0006
OL	GPP/R = -0.0018*T + 0.8011	R2 = 0.0056
WM	GPP/R = 0.0041*T + 0.6573	R2 = 0.0197

Note: Significant correlations are in bold text

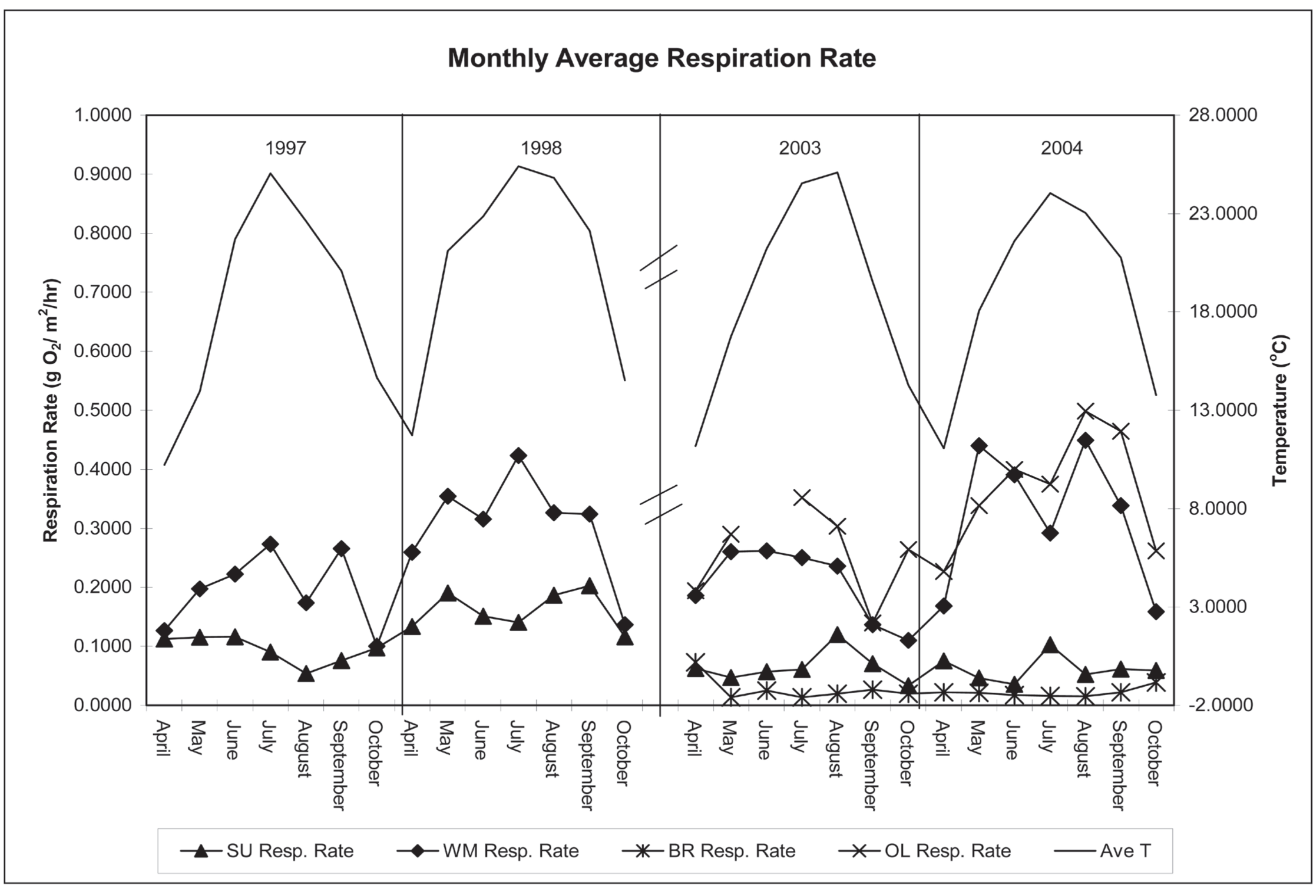


FIGURE 5. Monthly average respiration rates at sites SU and WM during 1997 and 1998 and at sites BR, SU, OL, and WM during 2003 and 2004 and average monthly water temperature from site SU.

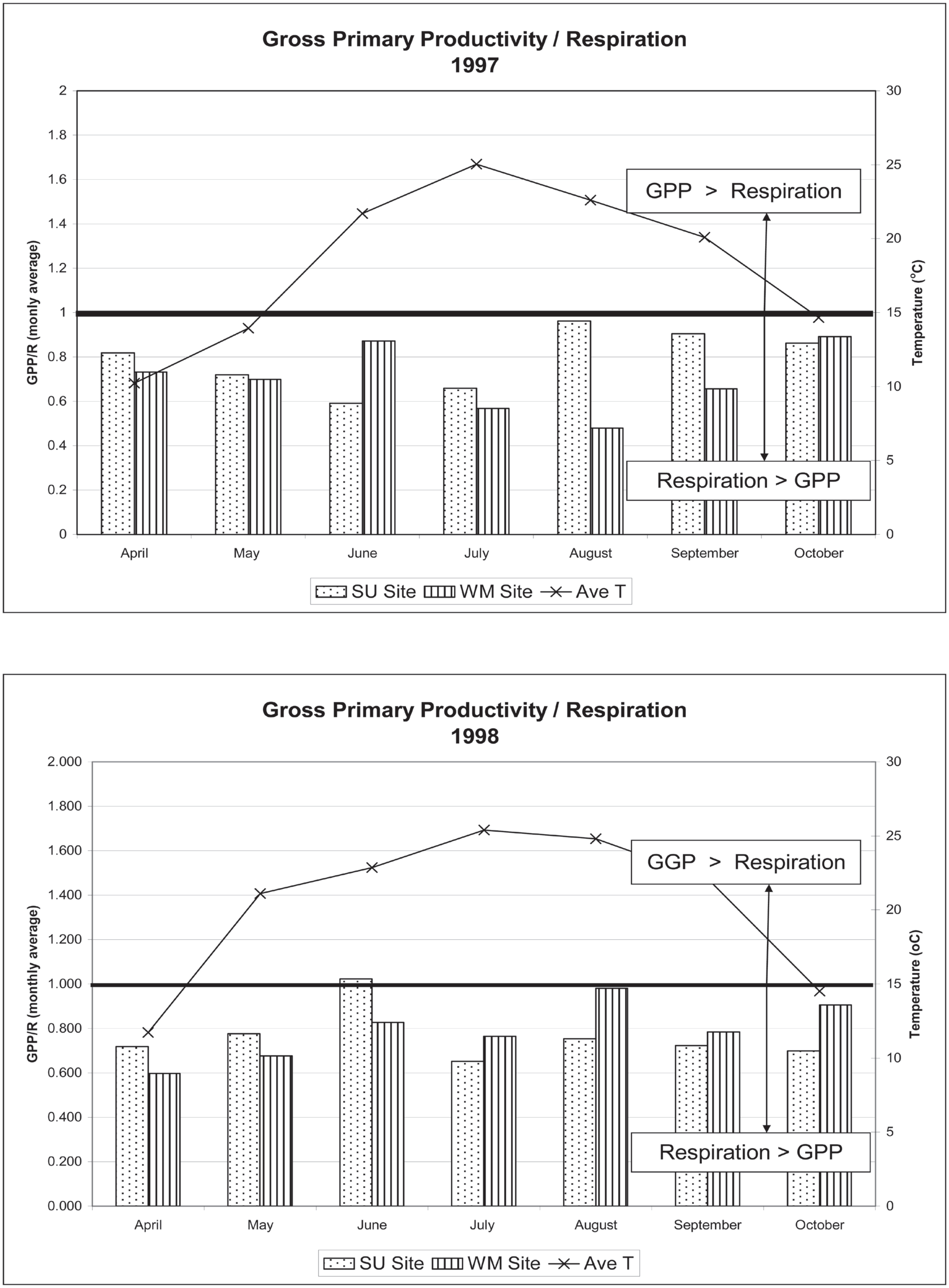
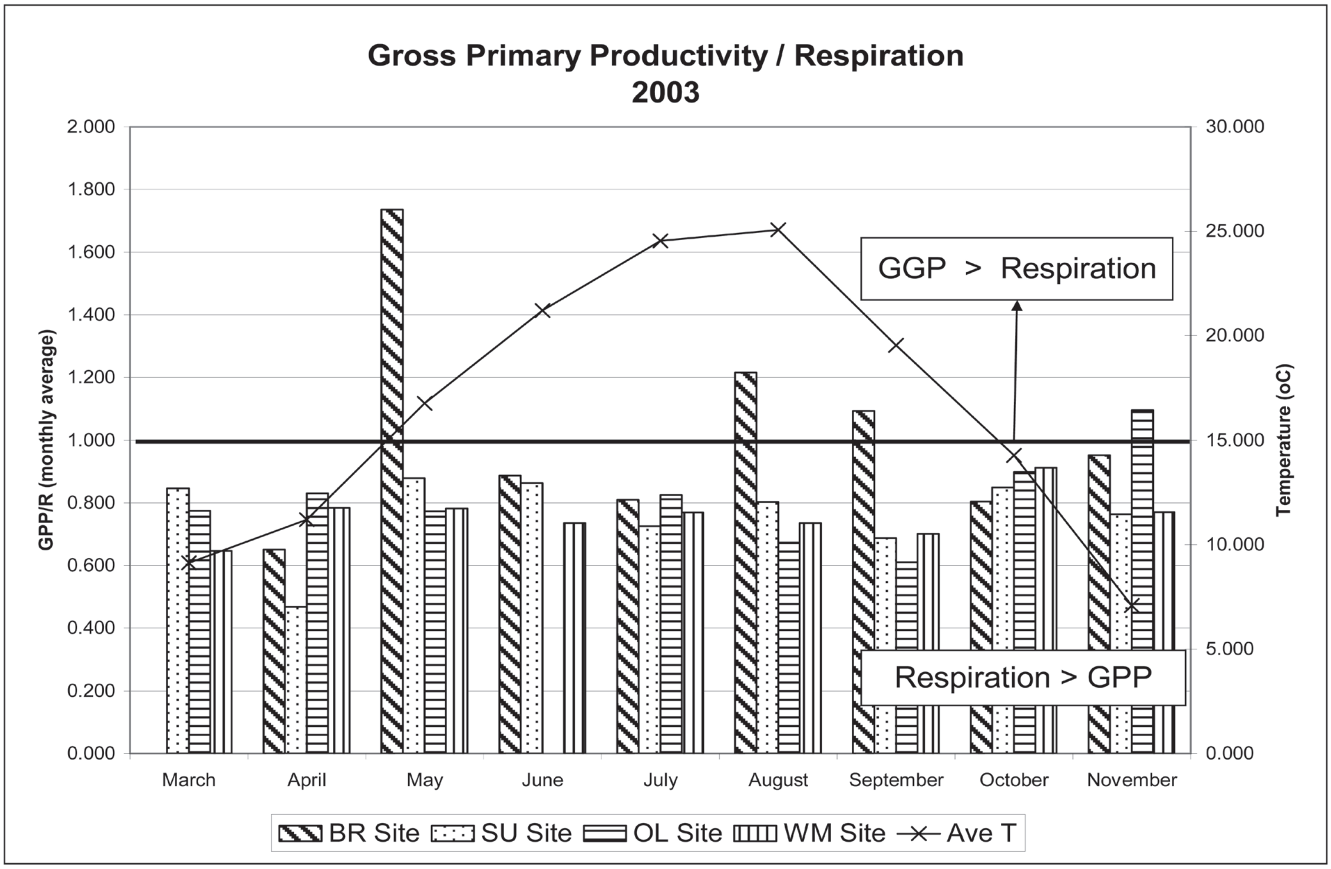


Figure 6. Monthly gross primary productivity/respiration ratios for sites SU and WM during 1997 and 1998, and average monthly water temperature from site SU.



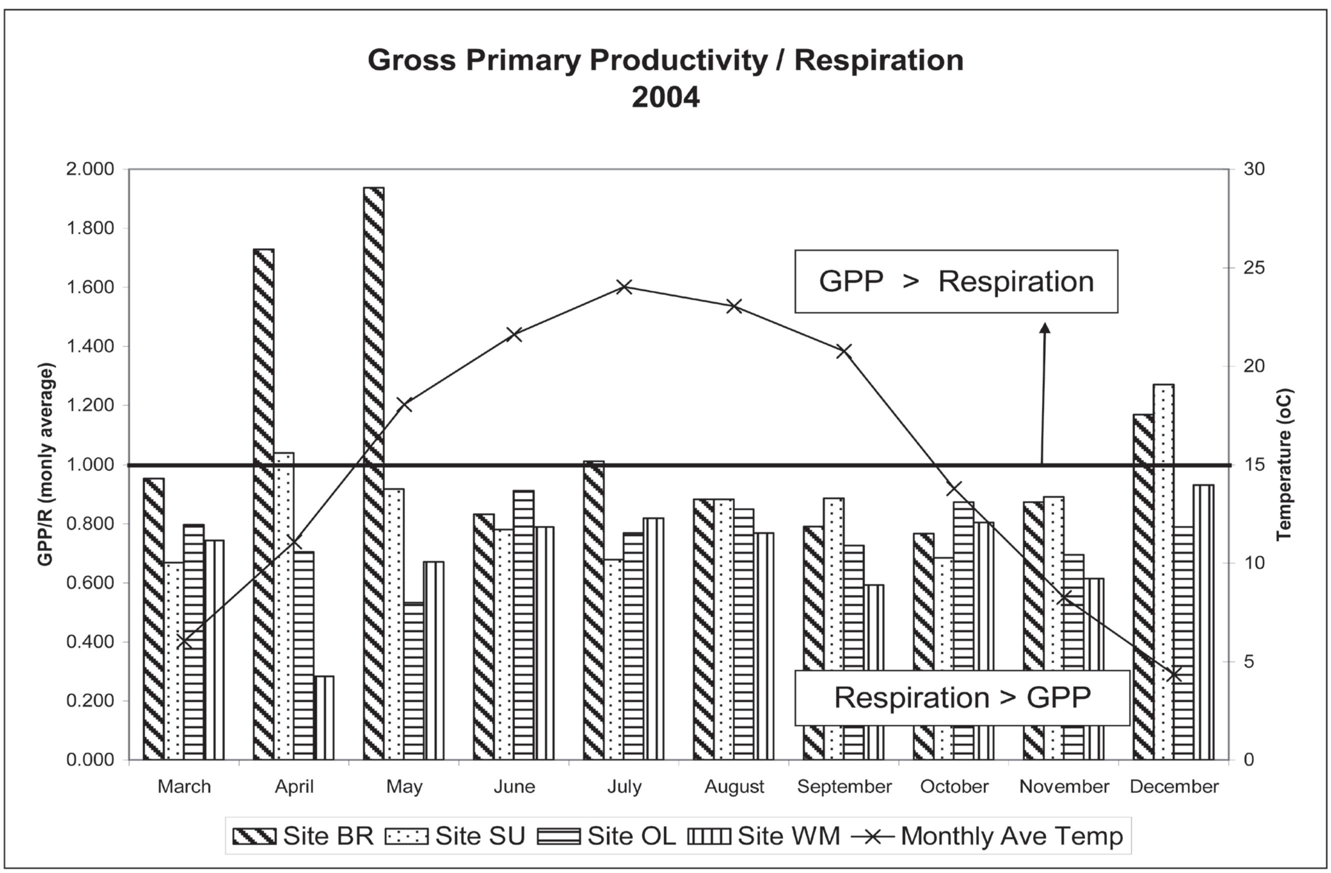


FIGURE 7. Monthly gross primary productivity/respiration ratios for sites BR, SU, OL and WM during 2003 and 2004, and average monthly water temperature from site SU.

(Table 1). Similarly, the average gross primary productivity was nearly the same for high and low lake levels: 4.9961 g O_2/m^2/day and 5.0626 g O_2/m^2/day, respectively.

Monthly average GPP/R ratios were normally less than one for all sites except for several months in the stream (BR) (Figs. 6 and 7). This suggests the system receives an external source of carbon, possibly from leaf fall (creek and upper estuary) and emergent macrophytic communities (lower estuary) both seasonally and during high and low water years. The mean monthly GPP/R ratio for high lake level years was not statistically different from low lake level years based on 2 sample t-Test analysis. For SU site, the mean monthly GPP/R was 0.7513 for high lake level years and 0.8015 for low lake level years (t=-1.2114, df=26, alpha=.05, P=0.1183, t_{crit}=1.7056). For the WM site, the GPP/R ratios for high and low lake level years were 0.7853 and 0.7978, respectively (t=-0.2746, df=26, alpha=0.05, P=0.3929, t_{crit}=1.7056). Gross primary productivity exceeded respiration only in the creek site (BR) during April and May, 2004 and May, August and September, 2003, and only once in the upper estuary (SU) during June 1998. Yearly average GPP/R ratios were less than one for all sites except the creek (BR) in 2003 (Table 1).

The change in computing respiration based on a five- hour night (2200-0300) versus a 12 hour night (1800-0600) interval had a small systematic effect on the GPP/R ratio at site SU and WM (Table 3). When the night time interval included some sunlight (1800-0600), the monthly average respiration was about 10% to 40% lower (eg.: SU site, July 2003, 1.2576 g O_2/m^2/day for night time interval of 1800-0600 vs. 1.5101 g O_2/m^2/day for night time interval of 2200-0300) and the GPP/R ratio is about 10% to 25% higher (Table 3). The mean of the monthly GPP/R for 2200-0300 time interval was 0.7735 compared to 0.9174 for 1800-0600 at the SU site (1997, 2003). Similar results were found for the WM site (Table 3). The difference in the means was found to be statistically significant using a paired 2 sample t-Test for SU and WM sites (Table 3). The GPP/R ratio still remains less than one for most months and sites tested (Table 3). Monthly average GPP/R ratios for all sites had no significant correlation with monthly average water temperature using least squares linear regression analysis (Table 2).

DISCUSSION

Wetlands generally have a detrital food web (Odum, 1971; Day et al. 1998), but zooplankton studies at OWC (Havens 1991a) have supported Reeder's (1990) contention of the significance of the phytoplankton and the resulting grazer food web in this estuary. This contradiction may be explained by work of Winberg et al. (1972) which demonstrated a shift towards phytoplankton dominance with increasing eutrophication. Since this estuary has been considered highly eutrophic (Havens, 1991b, Whyte et al, 2009), a phytoplankton based food web, would be expected.

During the summer and fall of 1988, Mitsch and Reeder (1989) examined changes in diurnal oxygen levels over three-to-six-hour intervals at nine selected sites in Old Woman Creek estuary. From the data, they calculated both production and P/R ratios for two sampling periods, July 12 and October 8-9, 1988. Several of their sites aligned well with sites used in the present study. Reeder and Mitch's upper estuary site 9 was located near the SU site, their lower estuary site 4 corresponds to the OL site, and their site 2 corresponds to site WM.

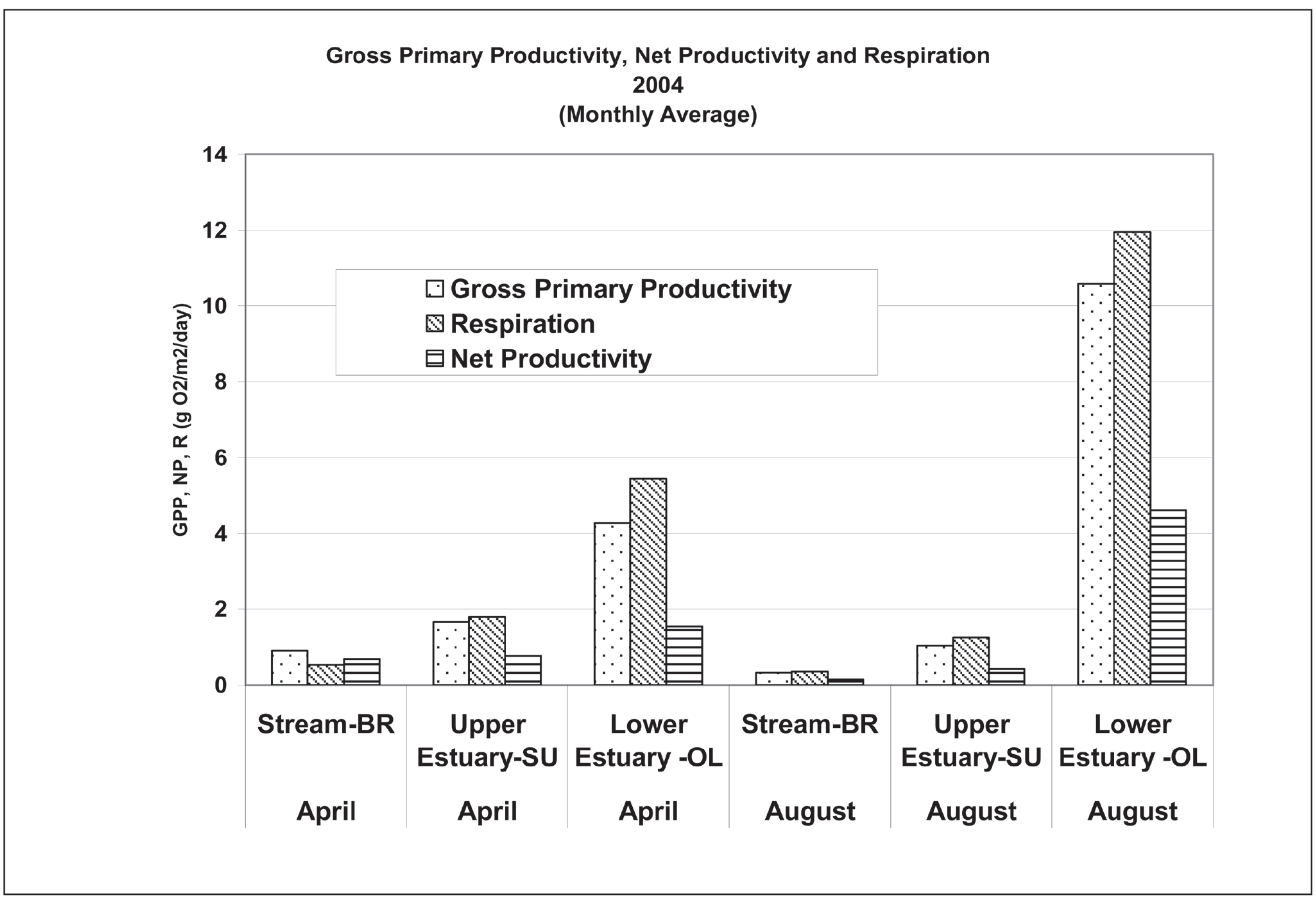


FIGURE 8. Seasonal comparison of monthly average gross primary productivity, respiration and net productivity during 2004 at sites BR, SU, and OL.

Table 3

Effect of night time interval on monthly average GPP/R and results of paired two sample t-Test for SU Site and WM site, 1997 and 2003

	GPP/R (Monthly Average)			
	SU Site	SU Site	WM Site	WM Site
Night Time Interval: Year Month	2200-03000	1800-0600	2200-0300	1800-0600
1997 April	0.9048	1.0415	0.7953	1.0415
1997 May	0.7490	0.6965	0.7175	0.8354
1997 June	0.5902	0.7972	0.8064	0.9613
1997 July	0.5230	0.8256	0.5682	0.5693
1997 August	0.8233	1.0485	0.5328	0.8205
1997 September	0.8203	0.9317	0.6920	0.8402
1997 October	0.8858	0.9026	0.8657	0.9028
2003 April	0.7412	1.0027	0.7844	0.9262
2003 May	0.8372	0.9182	0.7960	0.8779
2003 June	0.9235	1.0099	0.8168	0.9370
2003 July	0.7482	0.8220	0.7924	0.9652
2003 August	0.8534	0.9479	0.8199	0.9214
2003 September	0.6705	0.8793	0.8039	0.9667
2003 October	0.7582	1.0205	1.0487	0.9783
Paired Two Sample t-Test Results				
Mean	0.7735	0.9174	0.7743	0.8960
Variance	0.0136	0.0110	0.0155	0.0127
Observations	14	14	14	14
Alpha = .05				
Hpoth. Mean Diff.	0		0	
df	13		13	
t Stat	-5.2229		-4.9459	
P(T<t) one-tail	8.22082E-05		0.000133688	
t Critical one-tail	1.7709		1.7709	
P(T<t) two-tail	0.000164416		0.000267377	
t Critical two- tail	2.1604		2.1604	

Reeder and Mitsch (1989) found that gross primary productivity and respiration rates decreased from July to October 1988 due to decreased temperature. This same trend was observed in this study. As in the present study, Reeder and Mitsch (1989) reported that respiration exceeded productivity in the upper estuary site (GPP=4.07 g O_2/m^2/day, R=4.63 gO_2/m^2/day, July 1988). However, the values of gross primary productivity and respiration were higher in 1988 than in this study (GPP=1.43 g O_2/m^2/day, R=2.17 g O_2/m^2/day, July 1997).

In the lower estuary, the earlier work by Reeder and Mitsch (1989) and Mitsch and Reeder (1989) concluded that both sites during July had GPP/R ratios above one, suggesting that the system had a grazer based food web. In our study, however, both during the high water level period (1997/1998) and the low water period (2003/2004), the GPP/R ratio was below one, suggesting a detrital based food web. This difference may be the result of changing aquatic vascular flora in the estuary. When Reeder and Mitch conducted their studies, the lower estuary was primarily an open water system, with aquatic macrophytes accounting for only 20% of the surface area (Herdendorf et al 2006). By 1997 and 1998, the open water portions of the estuary had declined to about 60%, and macrophyte cover had expanded to 40% of the estuary surface. By 2003/2004, with falling water levels, open water accounted for only about 25% of the lower estuary while aquatic vascular plants covered the majority of the estuary (Whyte et al. 2008). With the increase in macrophyte abundance in OWC estuary from 1989 through 1997/8 to 2003/4, the detrital food web would become more dominant. During the high water period in the mid to late 1990s, Francko and Whyte (1999) supported our finding that the food web in the estuary was detrital based, as they determined that carbon fixation rates were five to ten times greater in the macrophytes than in the phytoplankton.

In the 1980s, the estuary had a grazer based food web, but with increasing macrophyte cover, the food web became detrital based (Herdendorf et al 2006). A detrital based food web could easily result in respiration rates being greater than gross primary productivity. Through the 1990s the dominant macrophyte in the estuary was *Nelumbo lutea* Willd. This species produces two cohorts of leaves, the first set float on the water's surface, and the second set are aerial leaves (Whyte 1996). If the leaf is above the water surface, the largest percentage of the oxygen produced by it during photosynthesis will be released to the air and would not be included when estimating photosynthesis by changes in oxygen levels in the water. When the leaf falls into the water, the bacteria, fungi, and animals in the water that feed directly or indirectly on this plant material would contribute directly to the community respiration. This could very easily result in a GPP/R ratio of less than one, as was found in this study. After 2000, the dominant aquatic macrophytes were emergent species, which would also release most of the photosynthetically produced oxygen directly into the atmosphere.

Other studies of estuaries or wetlands have reported that annual primary productivity rates based on changes in oxygen levels in the water are often less than the measured respiration rates. For example, in Jug Bay estuary, Maryland the annual gross primary productivity was 7 g O_2/m^2/day while the annual respiration rate was 14 g O_2/m^2/day (Caffrey 2003). Three of four experimental wetland basins in the Olentangy River Wetlands Research Park also had average respiration rates exceeding gross primary productivity rates (2.29 vs. 2.42 g O_2/m^2/day in Wetlands 1 Middle, 3.03 vs. 3.04 gO_2/m^2/day in Wetlands 2 Middle, and 3.08 vs. 3.10 g O_2/m^2/day in

Wetlands 2 Outflow) (Liptak and Mitsch 1999). Annual respiration exceeded gross primary productivity for all sites in the Old Woman Creek Estuary in 2003 and 2004 and the values are comparable to those reported by these other studies. This study, along with these earlier studies, highlights the importance of emergent macrophytes in the energetics of wetland systems.

The gross primary productivity/respiration ratio was generally less than one during the four years of this study, both during high water and low water periods. This suggests that an outside source of carbon was being utilized in the estuary during this period. This disproves our hypothesis that the estuary shifted from a grazer based food web to a detrital based food web when water levels dropped in 1999/2000. Although the drop in water levels did result in greater macrophyte cover, our data suggests that the shift from grazer to detrital based food web occurred some time before this water level drop, as the estuary was detrital based when we first sampled in the high water years of 1997/1998.

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